A layer-by-layer metallic photonic band-gap structure

J. S. McCalmont[a)]
Ames Laboratory, U. S. Department of Energy and the Microelectronics Research Center, Iowa State University, Ames, Iowa 50011

M. M. Sigalas
Ames Laboratory, U. S. Department of Energy and the Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011

G. Tuttle
Department of Electrical Engineering and Computer Engineering and the Microelectronics Research Center, Iowa State University, Ames, Iowa 50011

K.-M. Ho and C. M. Soukolis
Ames Laboratory, U. S. Department of Energy and the Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011

(Received 22 September 1995; accepted for publication 23 February 1996)

A new photonic band-gap structure has been developed using a periodic array of metallic rods. Structures have been designed and built that operate in the 75–110 GHz frequency range. A periodic structure shows a high-pass transmission characteristic, while the addition of a defect to the structure adds a bandpass response. Measured responses show good agreement with theoretical simulations. A defect mode operated in the reflection mode showed a quality factor Q of 461. This new metallic structure is considerably smaller than comparable dielectric photonic band-gap structures, and should be useful for building compact, inexpensive filters with operating frequencies ranging from 1 GHz to 1 THz. © *1996 American Institute of Physics.* [S0003-6951(96)03618-2]

Metallic meshes are commonly used as filters and reflectors for wavelengths ranging from microwave to infrared. Most of the research has focused on single layers of mesh, and the response of the layer has been modeled as a shunt impedance on a transmission line.[1–4] A metallic mesh is a specific example of a larger class of structures known as frequency-selective surfaces, which include not only mesh-like structures but also periodic arrays of metallic patches.[5–9] Frequency-selective surfaces are used as microwave filters; in randomes; as polarizers, beam splitters, and mirrors in the infrared; and have been suggested for use in solar energy collection.[6] Again, most of the results have been reported for single-layer structures, and no results have been presented for a true three-dimensional structure. Furthermore, the quality factor (Q) of the response of these structures has generally been very low.

There has recently been renewed interest in the characteristics of periodic metallic structures because of the intensive work on photonic band-gap (PBG) devices. These periodic dielectric structures exhibit frequency bands where electromagnetic waves cannot propagate; furthermore, the structures can be designed for a different frequency range simply by scaling their dimensions.[10] PBG structures have possible applications in filters, optical switches, cavities, and lasers. Most of the research effort has been concentrated in the development of PBG materials made from positive, frequency-independent dielectrics, because there are no potential difficulties related to absorption with these materials. At lower microwave and millimeter-wave frequencies, however, a metal acts as a nearly perfect reflector; this minimizes problems related to absorption and opens the door to a metallic PBG structure.[11,12] Additionally, the metallic structure can be made at a substantially reduced size and cost compared to a dielectric structure.

A new PBG structure made from stacked layers of metallic grids, as shown in Fig. 1, has been designed and fabricated. The grids, which are laterally aligned to each other, can either be free-standing in air or supported by dielectric substrates. The nominal grid pattern is a square lattice, although there is a great deal of flexibility in the shape of each cell of the grid. The transmission characteristic of this structure exhibits a band gap extending from zero frequency up to a cutoff frequency with as few as three unit cells in the stacking direction. The location of the band-gap edge is determined by the lattice constant, the width of the metal grid

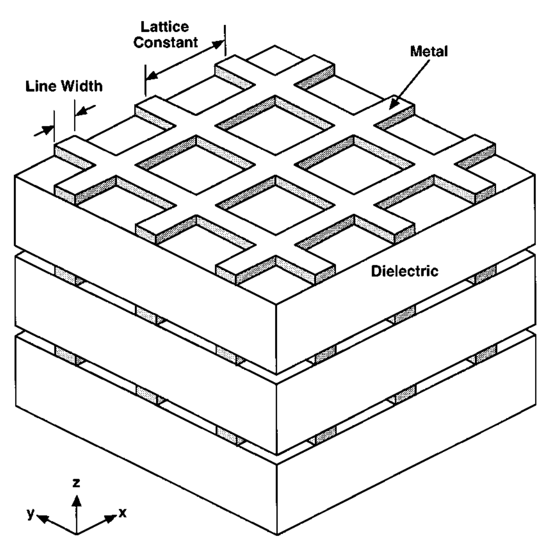

FIG. 1. Diagram of the metallic photonic band-gap structure. The response of the structure is determined by the lattice constant, the width of the metal lines, and the permittivity of the dielectric.

[a)]Current address: Electronic Technology Corporation, Iowa State University Research Park, 2625 North Loop Drive, Ames, IA 50010; Electronic mail: jsm@iastate.edu

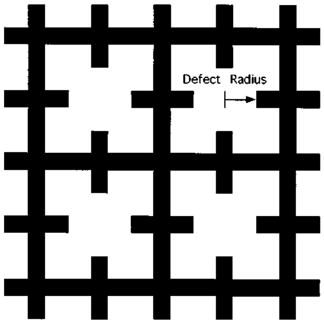

FIG. 2. Metal grid pattern for a defect layer. The frequency of the defect mode will be determined by the size of the defect, as given by the defect radius.

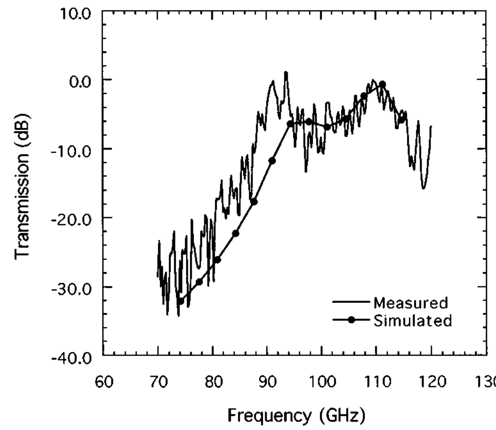

FIG. 3. Measured and simulated transmission response for a metallic photonic band-gap structure. The cutoff located at 92 GHz. The lattice constant of the structure is 0.800 mm and the linewidth is 0.200 mm.

wires, and the refractive index of the surrounding dielectric. A change in the periodicity of the center grid layer creates a defect mode in the band gap, effectively forming a bandpass characteristic. The defect pattern illustrated in Fig. 2 is formed by removing part of the metal grid at every other lattice point. The size of the defect, as measured by the defect radius, will determine the location of the defect mode frequency in the band gap. This tunability of the response characteristics is a new feature which, to the best of our knowledge, has not been explored by the studies of frequency-selective surfaces. This metallic PBG structure is similar to one previously suggested[13] except that in the present case there are no rods along the stacking direction. This makes the fabrication of the present structure much easier while the response of the structure is virtually unchanged over a wide range of incident angles.

The transfer-matrix method[14,15] (TMM) was used to calculate the electromagnetic transmission through the metallic PBG structure. With this method the total volume of the system is divided into small cells and the fields in each cell are coupled to those in adjacent cells. Then the transfer matrix can be defined by relating the incident fields on one side of the PBG structure with the outgoing fields on the other side. Although the band structure of an infinite periodic system can be calculated with the TMM, its main advantage is the calculation of the transmission and reflection coefficients for electromagnetic waves of various frequencies incident on a PBG structure of finite thickness. In that case, the material is assumed to be periodic in the directions parallel to the interface. The TMM has previously been applied in studies of defects in 2D PBG structures,[16] of PBG materials in which the dielectric constants are complex and frequency dependent,[17] of 3D layer-by-layer PBG materials,[18,19] and of 2D metallic PBG structures.[12] In all these examples, the agreement between theoretical predictions and experimental measurements was very good.

The structures were designed to operate in the W-band millimeter-wave region (75–110 GHz). This frequency range allows for a small device size while still allowing for relatively simple measurement techniques. These structures were fabricated from Rogers Corp. RT/duroid® 5880 microwave circuit board, a low-loss dielectric substrate with copper foil laminated to both sides. The duroid has a refractive index of 1.5 with negligible loss up to 110 GHz. One side of the copper cladding was patterned with the grid pattern using standard photolithography as is typically used in microelectronics fabrication. The backside copper was not patterned and was completely removed. Etching of the copper was done with a commercial $FeCl_3$–HCl–NH_4Cl printed-circuit board etching solution. Typically the etching solution was warmed to 50 °C to decrease the etch time. During etching, the solution was stirred with a magnetic stirring bar.

The millimeter-wave response of the structures in the 75–110 GHz frequency range was measured with a Hewlett–Packard HP 8510B network analyzer configured for W-band measurements. Transmission and reflection measurements of the magnitude and phase of the structures could be measured with a noise level below -60 dB.

Because the defect mode can be located at a frequency well below the cutoff frequency, it was not possible with the measurement setup to observe both the defect and the cutoff response with a single structure. Therefore structures with different dimensions were fabricated. One structure had a lattice constant of 0.800 mm with metal lines 0.200 mm wide, using 31 mil duroid with 0.5 oz. copper laminate (17 μm thick). This gives an expected cutoff frequency of about 100 GHz. The second structure, with a cutoff near 160 GHz, had a lattice constant of 0.544 mm with metal lines 0.100 mm wide, using 20 mil duroid with 1 oz. copper (36 μm thick). Defect modes for this structure lie in the 75–110 GHz range, where the exact frequency depends on the size of the defect.

Figure 3 shows a graph of the transmitted power versus frequency for the first structure. There is a clear band edge at 90 GHz. The average transmission in the cutoff region is about -40 dB, while at the band edge the transmission peaks at about -5 dB. The simulated transmission response shows good agreement with the measured data. At frequencies above the band edge the dip in the transmitted power is due to the next gap in the band structure. Note that the roughness in the measured characteristic is not random noise, but is caused by interference effects within the measurement setup. There are also some variations in the response due to disorder in the structure. This disorder comes from irregularities in the metal lines that originate in the etching process.

Figure 4(a) shows the transmission response of the second structure with defects of two different sizes in the second layer. A defect radius of 0.4a results in a peak in the trans-

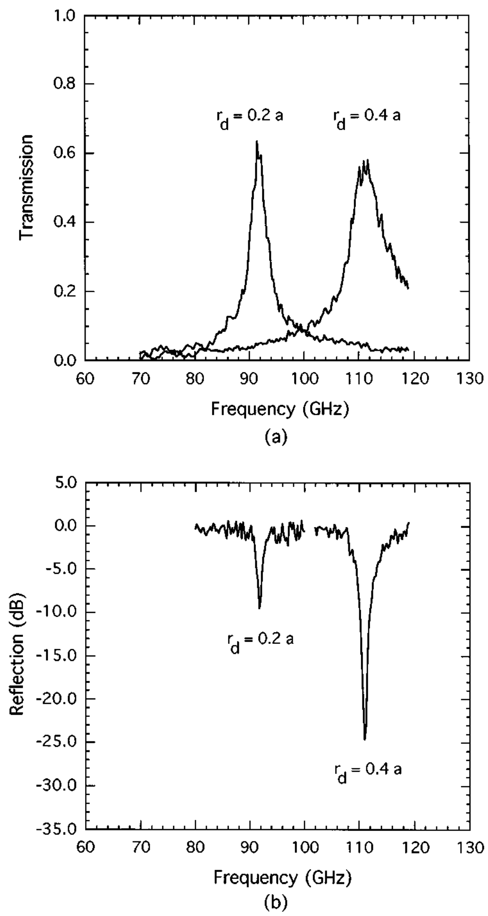

FIG. 4. (a) Measured transmission and (b) response for a metallic photonic band-gap structure with a defect in the second layer. The frequency of the defect mode decreases with the size of the defect. The lattice constant for this structure is 0.544 mm, while the linewidth is 0.100 mm.

mission at 111 GHz, while a defect radius of $0.2a$ gives a peak at 92 GHz. As the defect radius decreases, the defect mode shifts to lower frequency. The measurements were made at an incident angle of 45°, which not only reduces the interference effects seen with the first structure, but also permits the measurement of the reflected signal, as shown in Fig. 4(b). It can be seen that the reflected peak is much sharper than the transmitted peak, indicating that some absorption takes place at the band edge. The sharpness of the peak is measured in terms of the quality factor Q, where Q is the peak frequency divided by the 3 dB bandwidth of the peak. For the first defect $(r_d=0.2a)$ the Q of the transmission peak is 14, while for the second defect the Q is 23. The reflection peak of the smaller defect has a Q of 141, while for the larger it is 461. These results show that the response of the structure is significantly better when operated in the reflection mode. We believe that the value of Q would be larger if the disorder in the structure from the etching process were reduced.

Using the TMM, we calculated the defect frequency as a function of the defect radius. We used a supercell consisting of 2×2 unit cells along the x and y axes (see Fig. 1) with periodic boundary conditions along those axes; the system is finite along the z axis and contains three unit cells. Both theory and experiment show the same trend: by decreasing the defect radius, the defect frequency decreases. However, the calculated defect frequencies were around 15% smaller than the measured defect frequencies. This is probably due to the poor convergence of the TMM. Each unit cell has been divided into $N\times N\times N$ cells, where $N=10$. A high value of N would be needed for better convergence, but this kind of supercell calculation is time and space consuming.

Because the defect frequency of the metallic PBG structure is typically much less than the cutoff frequency, the metallic structure can be physically smaller than a dielectric PBG device operating at the same frequency. For example, a previously reported dielectric PBG operating at 92 GHz has a lattice constant of 1.6 mm,[13,14] whereas the metallic structure with defects reported here has a lattice constant of 0.544 mm for operation in the same frequency range. This factor of three reduction in size could be made even greater by substituting a material with a larger dielectric constant for the duroid. As with the dielectric structures, the frequency of operation for the metallic structure can be changed by scaling the dimensions of the structure. The advantages of the smaller structure size would be maintained during the scaling.

We thank E. Özbay, C. T. Chan, and R. Biswas for their help with this project. This work was supported by the Center for Advanced Technology Development at Iowa State University; the Director of Energy Research, Office of Basic Energy Sciences and Advanced Energy Projects; the Office of Scientific Computing as part of the High Performance Computing and Communications Initiative, including a grant of computer time on the Cray computers at NERSC at the Lawrence Livermore Laboratory and on the Paragon at Oak Ridge; and the Scalable Computing Laboratory, which is funded by Iowa State University and Ames Laboratory. Ames Laboratory is operated for the U.S. Department of Energy by Iowa State University under Contract No. W-7405-Eng-82.

[1] R. Ulrich, Infrared Phys. **7**, 37 (1967).
[2] L. B. Whitbourn and R. C. Compton, Appl. Opt. **24**, 217 (1985).
[3] J. A. Arnaud and F. A. Pelow, Bell Syst. Tech. J. **54**, 263 (1975).
[4] T. Timusk and P. L. Richards, Appl. Opt. **20**, 1355 (1981).
[5] *Frequency Selective Surface and Grid Array*, edited by T. K. Wu (Wiley, New York, 1995).
[6] R. Mittra, C. H. Chan, and T. Cwik, Proc. IEEE **76**, 1593 (1988).
[7] F. S. Johansson, IEE Proc., Pt. H **132**, 319 (1985).
[8] T. R. Schimert, A. J. Brouns, C. H. Chan, and R. Mittra, IEEE Trans. Microwave Theory Tech. **39**, 315 (1991).
[9] D. W. Porterfield, J. L. Hesler, R. Densing, E. R. Mueller, T. W. Crowe, and R. M. Weikle II, Appl. Opt. **33**, 6046 (1994).
[10] See the review articles in J. Opt. Soc. Amer. B **10**, 208 (1993).
[11] A. R. McGurn and A. A. Maradudin, Phys. Rev. B **48**, 17576 (1993).
[12] D. R. Smith, S. Schultz, N. Kroll, M. Sigalas, K.-M. Ho, and C. M. Soukoulis, Appl. Phys. Lett. **65**, 645 (1994).
[13] M. M. Sigalas, C. T. Chan, K.-M. Ho, and C. M. Soukoulis, Phys. Rev. B (1995).
[14] J. B. Pendry and A. MacKinnon, Phys. Rev. Lett. **69**, 2772 (1992).
[15] J. B. Pendry, J. Mod. Opt. **41**, 209 (1994).
[16] M. M. Sigalas, C. M. Soukoulis, E. N. Economou, C. T. Chan, and K.-M. Ho, Phys. Rev. B **48**, 14121 (1993).
[17] M. M. Sigalas, C. M. Soukoulis, C. T. Chan, and K.-M. Ho, Phys. Rev. B **49**, 11080 (1994).
[18] E. Özbay, E. Michel, G. Tuttle, M. Sigalas, R. Biswas, and K.-M. Ho, Appl. Phys. Lett. **64**, 2059 (1994).
[19] E. Özbay, G. Tuttle, M. Sigalas, C. M. Soukoulis, and K.-M. Ho, Phys. Rev. B **51**, 13961 (1995).